The Multiple Applications of 3D Printing: Between Maker Movements and the Future of Manufacturing

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Abstract In this chapter we point out how the general dynamics of decentralization and digitalization aggregate in two distinct ideal types of value creation: one updates the firm-based mode of a top-down approach and the other represents an alternative mode of bottom-up coordination that is more community-driven. For each mode, we contrast the most prevalent approaches to integrating novel technologies such as 3D printing and link them to innovative concepts of production. Having offered this distinction, we elaborate on associated manufacturing constellations and discuss the potential impact of hybrid arrangements.

1 Introduction

The socio-technical dynamics of digitalization indicate a possible regime transformation in the contexts of economic value creation as well as manufacturing. Comparing and contrasting the related trajectories and their associated options, we identify two distinct scenarios. The first scenario draws on existing patterns of value creation and the further development of production systems to increase digital networking and flexibility. The second, alternative scenario involves heterogeneous actor constellations and novel forms of self-organization such as the maker movement and the collaborative economy.

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The potentially opposing interests that shape these distinct scenarios are particularly evident in the context of new technologies and their application. In a commercial context, the manufacturing processes involved could represent elements of a globally networked production system (and thus not require significant modifications with respect to control structures); alternatively, they could constitute highly distributed patterns of production, fully independent of industrial infrastructure—still networked, but linked, instead, to organizational bottom-up structures. Between these two poles, researchers and practitioners should consider prospective hybrid configurations that ultimately combine society's demands for innovation with an urgently needed focus on sustainability. One of the major challenges of the 21st century, we believe, will reside in (actively) shaping the new economy at this crossroad between digital and material fabrication.

3D printing technologies play an exemplary role in both of the scenarios we outline, as they generally entail a radical customization and democratization of production, reduced transport costs through increasingly distributed value creation processes and on-site manufacturing, as well as a far-reaching fusion of the traditional producer and consumer roles. Visions of 3D printing thus suggest a radical decoupling of manufacturing processes and industrial infrastructure. The extent to which such "personal fabrication" or "desktop manufacturing" scenarios will actually be realized is difficult to assess. This is partially due to the nature of the current 3D printing hype, in which positive connotations abound: the 3D printer is viewed as the ultimate springboard for a number of highly diverse social groups and their own future visions (see Dickel and Schrape 2016). These include, for instance, the "democratization" of technology (Gershenfeld 2005; see Troxler 2016), more regionalized production with a more effective and sustainable deployment of closed-loop production cycles (see Ferdinand et al. 2016), or the emergence of new business models for the commercial production and supply of consumer goods (see Ihl and Piller 2016).

In this chapter, we aim to explore and discuss the complex technological and socio-economic trajectories of digital societies which are responsible for the current 3D printing hype. We start by describing general tendencies of digital value creation upon which possible shifts in production and consumption are based (Sect. 2). In the next section, we present two exemplary approaches to engage with these novel tendencies that point to either "top-down" or "bottom-up" modes for the coordination of value creation (Sect. 3). We further link these modes to new, decentralized concepts of manufacturing (Sect. 4). By comparing and contrasting different value creation models and their associated production options, we can imagine a scenario in which existing patterns of value creation essentially remain in place while progressing towards more digitally networked and flexible production systems. Then again, alternative scenarios involving novel forms of self-organization are also conceivable. Finally, along the continuum between these two scenarios, prospective hybrid configurations must be considered in order to grasp the full range of novel constellations (Sect. 5).

2 The End of Mass Production and Consumption?

The potential of digitalization and ubiquitous networking to revolutionize our systems of manufacturing and value creation has been noted at numerous junctures in the past decade (Koren 2010). A key aspect of this transformation is the re-negotiation of established producer and consumer roles: As consumers and potential users become increasingly integrated in the value creation process, we start to see a blurring of boundaries between product manufacturing and use, as well as new modes of participation (see, e.g., "user entrepreneurs" in Sect. 4.2) along the entire supply chain. This spectrum of new opportunities and producer-consumer constellations reveals a potential for transforming production systems in a way that makes them more sustainable. Given the serious environmental consequences of our established manufacturing regime, which is based on mass production and consumption, it becomes clear that rethinking production and consumption patterns will be a key factor in the realization of sustainable development.

The outlook for future development of the current value creation system has fundamentally changed; one major reason for this shift can be found in the widespread expansion of mass production and consumption after World War II, which occurred in an era characterized by the unlimited availability of inexpensive crude oil and widespread ignorance of the effects of associated material flows. Centralized manufacturing based on mass production and product standardization relies on the optimal utilization of scale effects. As this mode of production swept the globe and made products mass-marketable and accessible to broad segments of the population, it simultaneously increased our use of natural resources (with the resulting ecological side effects) to the unsustainable levels that currently threaten to exceed our planet's carrying capacity (see, e.g., Pfister 1995; Rockström et al. 2009). This situation demands a radical departure. Various approaches for establishing new, more sustainable forms of development have been proposed—green economy, circular economy, industrial ecology approaches, etc. These design challenges ultimately rely on transformation processes that change our social production and consumption patterns. Economic reasons for the structural transformation of the value creation process are to be found in more sophisticated product demand structures, as well as trends towards market saturation with respect to standard, off-the-shelf products. The effects of widespread digitalization combined with the emergence of new information and communication technologies are likewise driving the transition from mass production to more flexible production forms.

The sweeping changes brought about by digitalization have led to substantial reductions in transaction costs. Digitalization enables a heretofore inconceivable modularization and thus outsourcing of production; the hierarchical organization is questioned as the most viable mechanism for reducing transaction costs (Coase 1937). Radically reduced communication costs furthermore provide a basis for the integration of knowledge distributed among heterogeneous participant networks. With respect to organization, the source of innovation in value creation processes can also be outsourced in digitalized societies—out of the "classic" business firm and into “radically decentralized, cooperative, self-organizing modes of problem solving and production” (Lakhani et al. 2013: 365).

Organizations thus acquire access to the distributed knowledge of individuals and communities—an essential prerequisite for the implementation of concepts such as “open innovation” (Chesbrough 2008). At the same time, however, the superior position of the commercial enterprise in market-related innovation processes can also be threatened by this networking trend when the focus shifts towards decentralized networks, where innovative ideas circulate as non-commercial open-source knowledge (Al-Ani 2013). In the course of these developments, new forms of openness, collaboration, and decentralization have gained in relevance, questioning established practices of innovation in business (Bauwens et al. 2012) and greatly simplifying the distributed, networked participation of heterogeneous peer communities in developmental processes (Benkler 2006; Castells 2000).

Distributed networks thus offer a whole realm of possibilities for developing novel value creation concepts whose economic, ecological, and social potential has recently been the subject of much debate about sustainable forms of economic activity. The common thread in these debates is how centralized mass production can be replaced by smaller, independent, specialized local units; in other words, the much discussed sustainability approaches of the 1970s (“small is beautiful”; see Schumacher 1973), 1980s (“the end of mass production”; see Piore and Sabel 1985), and 1990s (“new work, new culture”; see Bergmann 1991) thus acquire new relevance as philosophical signposts on a road to a decentralized economy. In more recent times, ideals of a collaborative economy directly implicate aspects of digitalization and the growth of a networked society (see, e.g., Kostakis and Bauwens 2014).

3 New Concepts of Value Creation

With these broadly drawn conceptual trajectories, a closer look at specific options for implementing these new modes of value creation reveals two typical approaches representing either business-centric top-down organization or network-based bottom-up processes. Business-oriented approaches to enhance flexibility in production do involve modifications to traditional production and consumption patterns, but the control of value creation ultimately remains in the hands of organizations, which increasingly adapt digitalized production processes to meet specific customer demands. In contrast, bottom-up approaches contrive to offer a fundamental alternative to the current producer-consumer model by placing responsibility, not only for production but also the creative momentum of the product design, in the hands of potential users or user groups; as such, these actors can be viewed as early adopters of a radically decentralized system of production (Bauwens et al. 2012: 47 pp). Here, too, digitalization and network technology play an important role, but the user contexts in which they are employed are quite different from those of industrial applications. In the next section, we take a closer look at the key parameters defining the spectrum of new value creation, before focusing on the associated patterns of production (Sect. 4).

3.1 Top-Down: Mass Customization and Open Innovation

The gradual transformation from mass production to the fabrication of customer-specific products while maintaining the greatest possible efficiency has been characterized since the early 1990s as "mass customization" (Davis 1987; Pine 1993). Although the concept of mass customization has continued to evolve since its inception, it essentially deals with the question of how to design dynamic and flexible production processes capable of turning out quality products customized to meet the individual (or group) demands of customers at the best possible price (Piller 2004).

For several years, the implementation of mass customization approaches has remained largely conceptual, but more recently, ongoing technological improvements (particularly in IT and communications) have led to the deployment of some very specific approaches in manufacturer business models (Kumar 2008: 535; Piller and Ihl 2013). Continuous increases in the flexibility of commercial production systems, along with the resulting receptiveness of these firms to customer requests, has led to manufacturing processes that can efficiently turn out a wide range of products while at the same time ensuring a certain degree of flexibility in achieving certain specifications and modifications. In industrial production settings, such custom modifications are generally pushed back (postponement), allowing standardized processes to continue as long as possible and thus minimize the impact of custom specifications on the manufacturing process (Feitzinger and Lee 1997; Piller et al. 2004). Such strategies for the customization of consumer products offer the possibility of customer-specific, individualized approaches to product design, so-called "solution spaces." These spaces, however, remain centrally coordinated by business firms (see Salvador et al. 2009). Specific consumer preferences are therefore incorporated into production processes either through a direct information exchange between manufacturer and customer or through the use of software-based configurators. Thanks to the ubiquitous presence of digital media and devices, the use of configuration tools has expanded exponentially. The Cycledge database (http://www.configurator-database.com/database) currently lists almost 1000 various online configurators (as of July 2015) in numerous industrial sectors (e.g., apparel, automobile, electronics, entertainment, equipment for children, pet supplies, food, health, and industry).

In the context of mass customization, consumers assume an active role in distributed processes of value creation by articulating their individual preferences or participating in design and production processes. The economic viability of these concepts is in turn closely linked to the efficiency of the underlying production systems—in principle, customization can only occur when there is no undue increase in production costs. While it may still be economically viable to manufacture products that are personalized at a superficial level, that is, by using an online configuration tool (e.g., the selection of a custom color scheme to be applied to designer athletic shoes), this is not necessarily the case for those products requiring a highly customized form or fit.

The growing desire to customize standard products to meet the specific demands of various customer groups has reached the point that current and new approaches are increasingly focusing on “markets of one” (Gilmore and Pine 2000). In effect, the technological possibilities of individual product customization, at least in some areas (fashion, design in general, IT, etc.), mean that businesses can now fully personalize their consumer product offerings. Recognizing that the personalization of consumer offerings by means of more flexible communication, production, and logistics systems can also be efficiently achieved and thus open up new markets, some authors are already speaking of a shift from mass customization to “mass personalization” (see Kumar 2008; Ihl and Piller 2016).

Mass customization does generally address the trend towards product individualization, but with respect to its influence on production patterns, it remains embedded in traditional value chain concepts, in which the design and manufacturing processes are centrally coordinated by commercial firms. It is an example of a business-centric top-down approach to the challenges and possibilities of digitalization.

Other complementary forms of business-centric approaches are presented by “open innovation” strategies, where the goal is not to intervene in the later phases of value creation, but rather to involve external players in the early stages of product development. Open innovation thus marks a relatively new approach in innovation management, one based on opening up enterprise borders to impulses from outside the business environment. Of course, businesses have never been fully shut off from the outside world, but have always paid close attention to their environments and picked up on external influences and ideas. What has changed, however, is that the principle of open innovation has led companies to view their business environment more strongly as a strategic resource that may be of even greater relevance for innovation processes than their own internal knowledge resources. Knowledge production in line with the principles of open innovation is based on three ideas (Bartl 2008):

- Openness to the *assimilation* of knowledge from external stakeholders,
- *Collaborative production* of knowledge together with external actors,
- *Sharing* of knowledge with external actors.

Open innovation can involve integrating the knowledge other organizations and/or their employees. But it can also (and especially) arise through consumer participation in innovation processes, triggering a shift from consumer to “prosumer” (Araya 2008). Such an integration of prosumers into new product development processes is considered as a key factor for the success of product and service innovations. In each and every case, the integration of external integration is a matter of initiating processes to break through the traditional boundaries of communication, transaction, and participation that separate businesses and customers.[1] The intensity of interactions between producers and consumers thus becomes far more complex, and what once might have called for a mere articulation of preferences culled from a broad, but nonetheless (usually) circumscribed spectrum of possibilities and variations, now requires a give-and-take about the best approach to designing new solutions. By opening up areas of development that used to be kept strictly in house, manufacturers are hoping to achieve market advantages, especially by commercializing external innovation activities, as well as achieving an enhanced "market fit" with relevant target groups.

Although in concepts of mass customization and open innovation the distinction between producers and consumers is blurred, the primary responsibility for value creation in each case remains in the hands of the business firm.

3.2 Bottom-Up: DIY and Peer Production

In contrast to business-centric concepts of mass customization and open innovation, bottom-up approaches focus on decentralized network-based modes of value creation enabled by digitalization. Actors who previously had no access to self-manufacturing options for consumer goods have begun to revitalize alternative modes of personalized production. Decentralization, in this context, can refer to a spatial dimension (i.e., regionalization) as well as to the particular constellation of participating actors (leading potentially to a "democratization" of value (see von Hippel 2005)). The emergence of the so-called "maker movement" (Anderson 2012) can be seen as a renaissance of "do-it-yourself" (DIY) models of value creation—now, under digital conditions, often framed as "do-it-with-others" (DIWO).

The concept behind these various DIY, DIWO, or maker approaches has come to be known as "peer production" (Benkler 2006). Compared to the business-centric expansion of individual customer design options, peer production represents a substantially greater step towards personalized and decentralized value creation—production that no longer derives from a single commercial business, but relies instead on the community-based coordination of a heterogeneous "peer group" of participants. Value is thus largely created in a non-commercial environment and the resulting outputs can rarely be attributed to a clear owner or origin. Peer production emphasizes, accordingly, the free circulation of relevant knowledge (e.g. the "knowledge commons," see Helfrich 2012), as well as open and inclusive participation:

[1]Customers may want to participate in such value creation processes for various reasons. Reichwald et al. (2009) suggest that dissatisfaction with existing solutions and the prospect of satisfying individual needs in a product are just as likely to be the source of intrinsic motivation as anticipated social approval or external recognition, i.e., "pride of authorship", and/or external incentives such as monetary rewards or improved career prospects.

> "Projects have a common goal, and all participants contribute in one way or another to achieving this goal, because they share in the goals of the project, because they enjoy what they are doing, or because they want to give something back to the community. Market-based activities, on the other hand, consist largely of exchanges, usually of goods for money." (Siefkes 2012: 350).

Bottom-up, heterarchical (flat) networks emerge, with collaborative forms of cooperation among participating users (Al-Ani 2013; Benkler 2006; Zuboff 2010). In the digital realm in particular, *commons-based* peer production has become visible, a new mode which represents an alternative to the commercial marketplace and hierarchical organizations. It emphasizes—in the absence of centralized steering structures—community effort and open exchange. Baldwin and von Hippel (2010) similarly describe the resulting possibilities for cooperation: "An open collaborative innovation project involves contributors who share the work of generating a design and also reveal the outputs from their individual and collective design efforts openly for anyone to use" (ibid. 9). Although the authors here are referring primarily to the community-based development of open source software instead of the development and manufacture of material products, the ready availability of design software (Sketchup, Blender, etc.), as well as affordable access to production hardware such as consumer 3D printers supports that the growing relevance of the concepts they describe. Like freely accessible source code and looser restrictions on the copying and use of open source software, similar patterns of revealing and sharing product blueprints (object specifications, design plans, material lists etc.) can be observed for open hardware and open design. Within the context of DIY-related approaches, related patterns of producing and repairing material products have also been recognized as a new trend entailing socio-ecological issues of great relevance (Aachener Stiftung Kathy Beys 2012).

Al-Ani links the current renaissance of DIY to the structural nature of the developed capitalist society. Access to modern information media, increasing levels of technology, and lengthy courses of education, so goes the author's argument, awaken a creative potential in individuals that can scarcely be realized within the hierarchical organization. These individuals therefore seek an alternative means of expression, one that is removed from the traditional career path. Al-Ani describes a "cognitive surplus" leading to the growth of "free producers" in post-industrial societies (Al-Ani 2013; see also Shirky 2011). Following up on Benkler (2006), Al-Ani sees in Internet-based platforms the possibility of coordinating peer production, thus offering a productive channel for modern cognitive surplus without the need for centralized control or organizational hierarchies. Structured peer-to-peer (P2P) interactions produce value using platforms that are not only based on the commons in conceptual terms, but also built on commons-based output. This has led to the emergence of a collaborative economy (Bauwens et al. 2012) in which P2P continues to gain autonomy as it emerges from the virtual realm and establishes itself as a sector of growing economic importance. P2P will continue to co-exist with the market and state, but its borders may increasingly become more fluid.

In its rapid adoption of new technologies and utilization of diverse principles of modern organization and coordination, peer production eventually reveals potentially disruptive impacts (Benkler 2006; The Economist 2012; Strangler and Maxwell 2012). Indeed, numerous possibilities for the modification of value creation chains and more resource-efficient product design can already be identified. The significance of new technologies here is particularly evident in the case of the 3D printer. One aspect driving this development is the previously noted observation that bottom-up coordinated transactions do not function solely on the basis of marketplace logic, but also at a broader social level that includes the values and viewpoints of the participating actors.

Altogether, the models outlined above all rely on the emergent phenomenon of increasingly decentralized constellations for value creation, which may arise through technological innovations or due to changing values and individual user preferences. If we logically pursue these possibilities, it becomes clear that the affected participants—individuals as well as businesses—must respond to this transformation and shape it, whether by focusing on new working arrangements or new company policies. Likewise, consumers, in the case of decentralization, can play a bigger role in production, thus falling in line with the growing trend towards greater individualization and local products. As "free producers", individuals stand to gain more influence over the goods that are manufactured. In this respect, sustainability, collaboration, and social responsibility can serve as significant guideposts. Given the assumption that collaborative production in the form of grassroots innovation will continue to grow, it becomes essential to explore the extent to which the associated approaches and the potential they entail can be employed towards sustainable development (Smith et al. 2013).

4 New Patterns of Manufacturing

Having established the conceptual basis for new approaches to value creation, we now focus on the corresponding socio-technical constellations that might enable their immediate application in the area of (material) production. As was the case with the interplay of transformational dynamics in the area of value creation, on the production side of things it is possible to divide manifestations of these dynamics into two basic forms as well. First, we find, quite unsurprisingly, new technologies that influence the form and function of industrial infrastructure, including the implementation of potentially "smarter," globally networked production processes. Second, we can observe how peer production players are acquiring and/or appropriating similar technologies in their efforts to establish alternative patterns of value creation.

We discuss the implementation options for a presumably sustainable value creation approach with respect to each of the associated production systems. The heuristic distinction underlying this consideration is, on the one hand, the vision of bottom-up coordinated "peer communities" implementing value creation processes outside of established organizational forms of manufacturing. This is contrasted, on the other hand, with various constellations in which the logic of existing value creation patterns is essentially carried forward, but whose implementation options, however, are decisively expanded through the influence of new technologies (e.g., "smart factories"). As we will find, the following picture emerges: one path leads towards the further development of existing industrial concepts through the possibilities offered by new technologies. The second path contains alternative patterns of non-industrial production that adopt and apply the peer production concept to material manufacturing.

4.1 Top-Down: Industry 4.0 and Smart Factories

With respect to commercial, business-centric patterns of industrial production, the current trend for research and development lies in the area of smart "factories of the future," a concept designed to take direct advantage of digital technologies in the manufacture of material goods (European Commission 2013). Extensive digitalization and networking of production processes is seen as the key to meeting the contingent requirements of an increasingly dynamic production environment. Such contingencies within the production environment are a result of the myriad challenges facing manufacturers, who are no longer measured solely by efficiency, but also by their response to requirements of sustainability, as well as changing demand structures and ever more complex patterns of interaction. The combination of these aspects, which will intensify in the future, is deemed a critical success factor in global competition. This explains why funding initiatives such as the European "Manufacture" program and the US research program on "advanced manufacturing" currently are tendering and funding research in this area. In Germany, this discourse has been designated "Industry 4.0" (see Acatech 2013), implying a "fourth industrial revolution" after the earlier upheavals of mechanization, electrification, and informatization. Industry 4.0 paints the picture of a manufacturing industry as part of a networked, intelligent world, in which smart factories are interconnected nodes in digitally coordinated production networks.

The fundamental concept of "smart factories" consists of the widespread integration of production machinery in a comprehensive software architecture. This then serves as the basis for a fully networked integration of parts, machines, employees, and customers, as well as faster industrial production response times. Although this merging of production and information technologies has already been underway for more than 30 years, open "cyber-physical systems" (CPS) will help smart factories make the qualitative leap from piecemeal applications to a seamlessly integrated, networked landscape. CPS will not only coordinate internal factory manufacturing processes, but also structurally integrate these factories into global value creation networks (see Broy 2010). Broadly defined as "physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and coordination core" (Rajkumar et al. 2010), the potential of CPS in the context of manufacturing and production is to be found in particular in the interlinking of diverse components from various manufacturers, who are then able to undertake and process context-related tasks on a fully independent and self-organized basis. This homogeneous control approach furthermore makes it possible to readily adapt production systems in response to prevailing demand, execute change orders on short notice, and to further develop and maintain flexible manufacturing processes.

The production logic behind smart factories influences value creation at various stages in the product life cycle by enabling a comprehensive "interflow" of information between devices, machines, players, and service offerings. Product reviews, value chain management, and engineering take place continually over the entire development and production process. This may well lead to the development of new business models, but such new technologies may also simply be integrated into existing production systems and value chains. In accordance with the logic, resource productivity and efficiency in this context should "continually increase across the entire value chain network" (Acatech 2013: 5). The roadmap for this industrial transformation process can be summarized in three key points (ibid: 6):

- Horizontal integration via value-added networks,
- Vertically integrated and networked production systems, and
- Engineering consistency across the entire product life cycle

In the context of the smart factory, 3D printing has been adopted only peripherally, but increased implementation of related technologies is anticipated for the near to mid-term future. As generative manufacturing processes make strides in capability, efficiency, and affordability, 3D printing is likely to be implemented on a broader scale, particularly in the area of consumer goods, in the future. The industrial integration of 3D printing, it is widely assumed, will enable the cost-effective, decentralized production of an ever increasing array of individualized products, even in very small quantities (Lipson and Kurman 2013). In the area of consumer goods (primarily in design-intensive areas such as jewelry and interior furnishings), it is already possible to identify viable business models based on a service-oriented approach to generative manufacturing. Most companies look to a business model that allows customers to professionally produce various individually designed three-dimensional objects by means of generative processes. Alongside the market leader Shapeways (http://www.shapeways.com/) are competitors such as i.materialise (http://i.materialise.com/), Ponoko (http://www.ponoko.com/), and the German start-up trinckle (http://www.trinckle.com). In this sense, generative manufacturing processes supply the technological foundation for a radical realization of the "economies of scope" addressed by smart factories, as well as for the productive exploitation of the "long tail of manufacturing" (see Anderson 2007), where batch size is reduced to the one-off production of individually designed objects.

Although various individual components of smart factories are already in use, and context-sensitive, communication-enabled machines are occasionally integrated into factory infrastructures, the overall concept still serves more as a vision for research and as a guidepost for innovation policy and funding measures in the field. Basically, insights from our conceptual research efforts demonstrate that digitally networked production still faces significant challenges for the future, and extensive networking and distributed control of the various phases of the value chain are still in the early stages. In addition to the technological challenges, various non-technical issues such as cultural practices and the dimension of authority also need to be considered, as they will also transform power structures and chains of command in production.

With regard to strategies such as mass customization (see Sect. 3.1 above), which draw on new technologies to align the logic of mass production and consumption with demands for more responsive and personalized markets, the design approaches and development options outlined here also appear to advance the same trends towards informatization and automation that have existed for decades in the post-industrial context. Commensurate with this self-reinforcing character of future development, research and development goals in various countries primarily aim to safeguard international competitiveness. In Central and Western Europe, but also North America, it is assumed that the quality of production systems, particularly in the higher-end industrial sectors, will be maintained above all through greater flexibility (Koren 2010). Adaptive customization and responsiveness to changing patterns of demand, as well as the design of resilient value creation networks capable of rapidly adapting to complex and changing market conditions, are viewed as critical in the development of viable production systems for the future. In light of the gradual displacement of industrial world trade to East Asia that in recent decades has proven problematic for Western economies, it can be assumed that a comprehensive vision of digitally networked production systems in Western countries will not only involve securing the current situation, but potentially lead to a re-industrialization of these regions. Until now, aspects of sustainability and the ecological footprint of the emerging production systems comprise not much more than a side note to the current political and scientific discussions; the main concern is still improving efficiency.

4.2 Bottom-Up: Shared Machine Shops and User Entrepreneurship

Along this pathway of bottom-up approaches to collaborative value creation, new technologies and collaborative constellations can be wielded to establish new socio-technical constellations and independently exploit the wide-ranging possibilities of decentralized production beyond the established industrial infrastructure. In combination with new roles (makers, prosumers, etc.) and easily accessible fabrication technologies (particularly 3D printing), this spectrum of possibilities encompasses radical, individualized visions of “desktop manufacturing,” as well as sites of collective, community-based value creation, i.e., “shared machine shops.”

Shared machine shops (often called "makerspaces" or "hackerspaces") form an emerging network of collaborative production spaces and community workshops that offer users access to various fabrication techniques, and at the same time serve as the nuclei of local (albeit globally networked) "maker communities" (Moilanen 2012). Shared machine shops comprise, in this context, a decentralized infrastructure of tools and technological knowledge that supplies a community of tech "freaks," hobbyists, do-it-yourself tinkerers, and hackers with the necessary resources for collective learning and, with the autonomous production of individual products, an alternative to industrially manufactured mass-produced goods (Dickel et al. 2014).

Fabrication laboratories ("Fab Labs") are a particularly relevant form of the shared machine shop, specifying a minimal inventory of devices and machine tools necessary to implement the founding idea of "how to make (almost) everything" in any one lab (Gerschenfeld 2005). The first Fab Lab was installed in 2002 at the Massachusetts Institute of Technology (MIT); today there is a network of more than 300 active workshops (http://wiki.fablab.is/wiki/Portal:Labs) throughout the world (see also Troxler 2016). In 2007, an international Fab Lab charter was adopted, establishing the essential principles of the Fab Lab form—e.g., public access to tools and knowledge (http://fab.cba.mit.edu/about/charter/). Along with the integration of the local site into a global network of collectively shared or usable workshops, the sharing of knowledge in accordance with the motto "make—learn—share" forms a further key aspect of the Fab Lab ideology. Technical and production expertise are to be passed on and shared among all users, so that ideas and concepts can be further improved through community participation and the pursuit of an open design process. This also includes ecological aspects like "sustainable and innovative problem-solving approaches" (ibid.) and recycling as an "integral element of production" (Gerschenfeld 2011: 76; see also Dickel et al. 2014). Furthermore, Fab Labs endeavor to increase the problem-solving capacities of laypeople by means of digital fabrication; "Instead of bringing information technology (IT) to the masses […] it's possible to bring the tools for IT development, in order to develop and produce local technological solutions to local problems" (Gershenfeld 2005: 13). This is highly relevant in less developed countries, where projects of a utilitarian value aim to improve local living standards. For example, in Pabal, a small village in India, sensors for measuring the fat content of milk (which determines the selling price) and tuning kits for diesel motors are currently being manufactured; labs in Ghana turn out automotive parts and agricultural implements; and in Norway, radio chips are produced that allow for the tracking of reindeer herds (see Friebe and Ramge 2009: 123).

Shared machine shops embody hopes of a more decentralized mode of manufacturing. The most radical vision of decentralized production is, however, the concept of desktop manufacturing. In desktop manufacturing the means of production are not a collective resource, but rather distributed among autonomous individuals possessing the technical resources for production. Analogies are often drawn to desktop publishing. Thus stakeholders in the area of 3D printing are continuously reminded that, akin to the desktop printer, corresponding end-user devices, i.e., "desktop factories," will one day be as widely distributed and commonplace on office desks as the inkjet and laser printers for home use that preceded them (Anderson 2012).

Although the increasing diffusion of 3D printers into consumer electronics has so far not led to any radical changes in or developments to the technical processes, the business of manufacturing 3D printers is in a state of flux. The first RepRap and MakerBot printers arose in communities of researchers, hobbyists, and hackers, whose participation in the technical development was closely aligned with the ideals of the open-source and maker movement; today, however, as the focus turns to the consumer market, the manufacture of 3D printers is increasingly directed by commercial manufacturing firms (see also Tech et al. 2016). The range of prices for 3D printers is thus expanding along with the spectrum of devices being offered for sale. While simple models such as the micro 3D printer can be had for just under US$300, the fifth-generation MakerBot Replicator currently costs almost US$3,000.

"Making" in general and 3D printing in particular are local and physical *and* global and virtual. Although the physical realization of various products and objects occurs locally and even involves some cases of radical customization, the respective value creation processes are for the most part embedded in broader, digitally networked utilization contexts. Thus, in addition to the documentation of a product's development in the form of tutorials, design drawings, etc., the online circulation of these documents comprises an important aspect of the maker code of practice. Internet platforms such as Thingiverse (http://www.thingiverse.com/), Instructables (http://www.instructables.com/), or Github (http://github.com/) are based on social media architectures that make possible the effective and far-ranging publication and distribution of product blueprints as "open-source hardware" within the various communities.

Along with these non-commercial and commons-based forms of adoption, various opportunities for "user entrepreneurship" (Shah and Tripsas 2007) are also arising at the intersection between the maker movement and shared machine shops, thereby providing individuals with the means to commercially develop their own product ideas while avoiding the traditional hurdles in the process manufacturing industry (e.g., large capital investments) or the necessity of external industrial exploitation. User entrepreneurship makes it possible to channel the extensive and widely distributed innovation potential within the maker communities into new and original products, business models, and previously unexplored branches of business; as a consequence, bottom-up modes of value creation are beginning to acquire a certain economic relevance that might continue to increase in the future. At the same time, crowdfunding enables a platform-based opportunity for decentralized project and product financing, which, thanks to the large-scale participation of individuals, offers the "user entrepreneur" a relatively low threshold of access to financial support.

5 Transitions

Value creation and manufacturing are in the grips of a transition. New information and communication technologies imply far-ranging reconfigurations that will also affect patterns of production and consumption. We have seen that the requirements for the design and development of production systems are becoming more complex and that along with traditional criteria for efficiency, new standards for responsiveness, flexibility, and customer awareness must also be met. One key aspect is that the implementation of decentralized production patterns will be made easier thanks to new technologies such as 3D printing. This, at least initially, would seem to contest the role of large companies in innovation, production, and consumption. It also poses new challenges for the conceptual transformation of value creation processes. Proceeding from the broad spectrum of new constellations that have arisen, we compared and contrasted two representative trajectories or patterns of value creation.

The business-centric trajectory (including approaches like mass customization, open innovation, and smart factories) certainly implies substantial transformations in industrial production, but not necessarily the development of vastly transformative trajectories such as collaborative design options in production and consumption. In general, it appears that the degree of individualization (ascertained by the intensity of producer-consumer cooperation) could have a decisive effect on the distribution of production, although products involving relatively superficial specifications, managed via IT-based product configurators (e.g. designer sneakers with custom color schemes), can still be produced in the established industrial regime. Thus it can be assumed that branches such as the automotive industry will increasingly turn to decentralized innovation and production, and thus implement smart factory concepts which are likely to include the professional application of 3D printing technologies.

Alternatives to industrial, business-centric value creation can be found in bottom-up approaches, which focus instead on decentralized, collaborative patterns of production that unite various sources of transformative potential. The associated forms of value creation are supported by two structural trends: (1) peer production in the digital environment, and (2) a renaissance of the do-it-yourself culture in material production. These two trends continue to become more closely intertwined: For one thing, knowledge about the skills and information required for DIY fabrication and repair projects is increasingly exchanged online and thus made globally accessible. At the same time, decentralized, digital fabrication technologies —above all 3D printers—are becoming increasingly affordable for the DIY community. Users can already draw on an abundance of online design templates (based in part on scans of actual products) and locally transform these into material objects.

It should not be assumed, however, that the dynamics outlined here will lead in the short- to mid-term to a complete disruption of established value creation patterns; nor is the boundary between the two developmental options so clear-cut. Between the two options of professional enterprise and/or industrial manufacturing versus peer production and desktop manufacturing, a range of hybrid constellations incorporating various players is possible (in this volume). This can also involve an intertwining or meshing of top-down and bottom-up forms of coordination. While the ideal-typical distinction between a profit-oriented business approaches in contrast with a commons-based community effort is relatively clear, a broad spectrum of possibilities can be found between these two models. The advent of commercial makerspaces like TechShop demonstrates that complex interdependencies and interactions between business and local DIY communities are already a reality.

As regards to environmental aspects, the current trend towards decentralization offers some potential opportunities, but these should not be overestimated. While the environmental effects of the technological impacts remain ambiguous, it is, above all, the manner in which technological opportunities become socio-economically embedded that could contribute to a change of course toward more sustainable development. This is a matter not only of individual innovations, but also modifications of infrastructure and the associated behavioral changes in an increasingly volatile environment, where new technological potential meets new forms of social networking. In this respect, the 3D printer, although at present scarcely able to live up to its own hype, embodies the material and symbolic convergence of technical and social considerations for a decentralized system of innovation.

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